An integrated approach for seismic characterization of carbonates

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Scientific environment

The work presented in this dissertation was carried out during my Ph.D. study in the period of January 2007 to June 2010 at the Department of Earth Science (DES) University of Bergen (UiB). This project has also been a part of the Carbonate Reservoir Geomodel at the International Research Institute of Stavanger (IRIS) and counts for four papers. The project was financed by the Norwegian Research Council Petromax Program under contract 163316. The supervisor of this project has been Professor Tor Arne Johansen with co-supervisor of Professor Mike R. Talbot both at DES.

This dissertation comprises two complementary parts. The first part gives a general description of the encountered problems in carbonate reservoir characterization along with the strategies that has been applied during this thesis to overcome these problems. During this part, I will try to illuminate the thread between the four papers which deal with different aspects of carbonate seismic reservoir characterization. The second part, which is the main outcome of my study, is a collection of four research papers. The papers will be referred to numerically as 1-4 and are submitted to different journals. Therefore, they follow different styles and formats in accordance with the journals requirements.

The preliminarily results of paper 1 was presented at the 70th EAGE conference in Rome 2008, and is published in 'Petroleum Geoscience', volume 15 (4), pp. 355-365, 2009. The preliminarily results of paper 2 was presented at the 78th SEG conference in Las Vegas 2008, and is accepted for publication in the 'Open Geology Journal'. Other presentations regarding rock physics modelling of chalks were held at the chalk workshop in Stavanger 2008, and in Gargano, Italy 2008. Paper 3 is under revision for publication in 'Geophysics', while preliminarily results of paper 4 were presented in the 'Sound of Geology' workshop in Bergen 2009 and is in preparation for submission to 'Geophysical Prospecting'.

Acknowledgements

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Introduction

Carbonate rocks constitute as much as 19-22% of the sedimentary rock records while they account for approximately 50% of oil and gas production worldwide. They may form from biological, biochemical, and/or inorganic precipitation of $CaCO_3$ from sea water and can appear as reservoir rocks, intermediate layers or even reservoir seals. However, carbonates are characterized by their heterogeneous rock properties which make the seismic responses more ambiguous than in siliciclastic rocks. Thus, there are more seismic challenges with carbonate rocks exploration and developments for hydrocarbon recovery than with siliciclastic rocks.

The main reason for such ambiguities in the carbonate elastic behaviors can be related to their tendency for having highly variable and complicated pore systems (e.g. Wang 1997; Anselmetti and Eberli 1999; Assefa *et al.* 2003; Adam *et al.* 2006; Baechle *et al.* 2009) which is a result of their processes of formation. Depositional environments define depositional textures of the sediments, while subsequent diagenetic alterations modify these textures and create complex rock properties such as porosity and pore types (Anselmetti and Eberli 1997). Therefore, constraining and calibrating seismic data with geological information may help with a better characterization of reservoir properties in carbonates.

The objective of this Ph.D. thesis is to increase understanding of the interplay between geological processes and seismic rock properties in carbonates. This involves the study of geological processes in carbonates, and then the development of some strategies for incorporating these geological processes into rock physics models and seismic characterization methods. Therefore, it requires an integrated study with a detailed insight in carbonate formation processes, rock physics models and seismic characterization methods. To achieve this goal two different datasets from the western equatorial Pacific (Ontong Java Plateau) (paper 1 and 2) and the Barents Sea (Finnmark Platform) (paper 3 and 4) have been made available during the study.

Paper 1 of this Ph.D. thesis concerns the depositional and post-depositional (diagenetic) effects on velocity modelling of chalks. Chalks are deep-water pelagic sediments consisting largely of stable low-magnesium calcite (e.g. Hamilton *et al.* 1982; Morse and Mackenzie 1990). Progressive diagenesis makes changes in their depositional pore geometry (e.g. Kim and Manghnani 1992) and reduces their initial porosity (e.g. Fabricius *et al.* 2007). The pore structure changes are modelled in this paper using an inclusion model based on the self-consistent approach, and by using chalks formation processes (ooze, chalk and limestone). Modelling results indicate that mechanical compaction and cementation decrease porosity as a function of depth, but may increase the velocity by different rates as one process can soften, and another stiffen, pore-models, respectively. In this paper, we present a strategy to model diagenetic history of chalk velocities using inclusion based models, and considering chalks depositional textures.

The strategy introduced in paper 1 for pore-model construction is applied in paper 2 to build a background velocity model based on information about the lithologies and the velocity data from some reference wells. Furthermore, this approach is used to obtain a gridded velocity model of a reservoir sequence and to predict velocities at some so-called blind wells. The applicability of one of the pore-model attributes, namely the pore-model stiffness (*PMS* value) is examined for velocity prediction. The good match between predicted velocity using the *PMS* value and measured velocity proposes a useful parameter for seismic characterization studies. The rock formation history, elastic behavior and porosity information all are incorporated in this parameter ($0 < PMS \leq 100$) which controls both P- and S-wave velocities and (V_p/V_s) ratio and as a result Poisson's ratio of the rock. Moreover, this parameter can be incorporated into the reservoir gridded model along with other reservoir properties (e.g. porosity, permeability) for reservoir characterization purposes.

Quantifying the effects of pore fluid on reflection seismic by considering variability in the elastic behaviour of carbonate rocks is the theme of paper 3. This paper deals with reevaluation of the frequently used fluid display attribute in siliciclastics called fluid factor, for carbonate rocks. We modify the fluid factor equation for a better linearized background relationship by using V_p^2 vs V_pV_s crossplots instead of V_p vs V_s crossplots. Furthermore, the modified fluid factor equation, along with other fluid factor equations, is used to extract fluid factor images from a seismic section along a line between two wells which covers a possible partially gas-saturated carbonate layer embedded within a water-saturated carbonate sequence of the Barents Sea. It can be seen that the modified fluid factor displays the gas-saturation brighter than other alternatives, although, in this case, all the studied indicators perform well and consistently. The results are also confirmed by the well logs at the end points of the seismic line.

Paper 4 focuses on the fluid substitution problem in carbonates using Gassmann's (1951) relations. Laboratory measurements of 23 carbonate core plugs from two exploration wells in the Barents Sea were used during this study. The velocity-porosity trends for different depositional environments along with the 'velocity deviation' term (Anselmetti and Eberi 1999) are proposed for defining a kind of geology dependent pore-model to be used in an inclusion model based on the self-consistent approach (SCA). Furthermore, these pore-models should be adjusted to achieve a consistency between SCA, the simplified Gassmann equation (e.g. Mavko and Mukerji 1995; Han and Batzle 2004; Rasolofosaon and Zinszner 2004) and a similar relationship for the shear modulus when pore fluid bulk modulus is altered. Our results confirm that rocks containing microporosity and cracks (weak pores) are prone to give wrong velocity predictions when altering the pore fluid bulk modulus (Adam *et al.* 2006; Baechle *et al.* 2009). A linearization procedure is proposed to modify a pore-model for fluid substitution. This procedure increases the number of pore aspect ratios (ellipsoids) in the pore-model, which provides a better pore structure description of rocks with complex pore geometry.

List of publications

Paper 1: Saberi, M.R., Johansen, T.A. and Talbot, M.R. (2009): Textural and burial effects on rock physics characterization of chalks. Petroleum Geoscience, Vol. 15 (4): 355-365.

Paper 2: Saberi, M.R. and Johansen, T.A. and Sælen, G. (2010): Rock physics interpolation used for velocity modelling of chalks: Ontong Java plateau example, review accepted for publication in the 'Open Geology Journal'.

Paper 3: Saberi, M.R., Johansen, T.A. and Ruud, B.O. (2010): Revisiting the seismic fluid factor: A carbonate case study, under revision for publication in 'Geophysics'.

Paper 4: Saberi, M.R. and Johansen, T.A. (2010): Velocity effects of fluid substitution in carbonates: example from the Barents Sea, in preparation for submission to 'Geophysical Prospecting'.

EAGE extended abstract (1): Saberi, M.R., Johansen, T.A. and Agersborg, R. (2008): Pore geometry as an indicator of depositional texture and velocity variations in chalks: 70th EAGE conference and exhibition, Rome, Expanded Abstract A014.

SEG extended abstract (2): Saberi, M.R. and Johansen, T.A. (2008): Rock physics interpolation used for velocity modelling of chalks: Ontong Java Plateau example: 78th SEG annual Meeting, Las Vegas, 1685-1689.

Contents

1. Carbonate geology

The wide variability observed in the porosity-permeability crossplots of core-analysis data indicates a high degree of petrophysical heterogeneity in carbonate reservoirs (Lucia *et al.* 2003). These extreme petrophysical heterogeneities in porosity and permeability are caused by the high degree of the carbonate geological heterogeneity which comes from their process of formation (Jardine and Wilshart 1987). Such heterogeneities will make the elastic behavior of carbonates more complex than that of siliciclastics (Anselmetti and Eberli 2001). Hence, resolving carbonate geological heterogeneities which comes from the variety in their processes of formation may help with a better understanding of their ambiguous elastic behaviors.

1.1 Carbonate depositional and post-depositional environments

Depositional environments determine the starting conditions for carbonate sediments to undergo diagenetic alterations and control the intrinsic parameters of carbonate rocks, such as porosity, pore type, density and mineralogy (Anselmetti and Eberli 1997). The depositional texture and composition of carbonate rocks are very sensitive to changes in oceanographic conditions which includes several factors such as water temperature, salinity and nutrients, water depth etc. (Hamilton *et al.* 1982) and differ from place to place (Jardine and Wilshart 1987). Thus, the depositional texture and composition of carbonates, which determine carbonate reservoir properties, varies in different depositional environments based on their oceanographic conditions. Dunham (1962) used depositional textures along with the amount of matrix surrounding the grains at the time of deposition to define a classification for thin section description. Moreover, Wilson (1975) defined a standard facies model for a rimmed platform based on depositional condition. These depositional based classifications can provide a good basis for characterizing carbonate rocks in terms of their complex depositional conditions and textures.

Furthermore, these depositional textures are modified by diagenesis. Diagenesis commonly begins as soon as carbonate sediments are formed (Mcllreath and Morrow 1990) and includes all changes in the sediments that take place after deposition. Tucker and Wright (1990) define these changes through three major diagenetic environments: marine, near-surface meteoric and burial environments. Marine diagenesis takes place on the sea floor and just below, and on tidal flats and beaches. Meteoric diagenesis can affect sediments soon after deposition, while the burial environment is from below the zone affected by surface processes, tens to hundreds of meters depth, down to several thousands of meter or more, where the zone of metamorphic dehydration reactions is reached. In the shallow subsurface, at the interface between marine and meteoric waters, Tucker and Wright (1990) defined the forth diagenetic environment as the mixing zone. However, carbonate sediments may pass from one of these environments to another with time of deposition and burial, sea-level changes and/or vertical tectonic movements.

1.2 Carbonate porosity and pore systems

The porosity of carbonate sediments shortly after deposition is very high (50%-80%) (Tucker 2001). This primary depositional porosity is progressively modified during burial through a number of interrelated diagenetic processes. The porosity is lost through cementation and compaction and gained through dissolution, dolomitization, and fracturing. Therefore, porosity can be divided into two main types in carbonates: primary (depositional) and secondary (post-depositional). Primary porosity is any porosity present in a sediment or rock at the termination of depositional processes and can be determined form depositional texture. Secondary porosity is developed at any time after final deposition and is predictable based on primary mineralogical composition, texture and diagenetic history. In brief we may say that both types of porosities are commonly facies controlled, and facies are controlled by depositional environments (Moore 2001).

Pore systems in carbonates are also much more complicated than in siliciclastics (Lucia 1995). This complexity is a result of their biological origin and their high susceptibility to chemical reactivity (Moore 2001). Chemical reactivity actually results in the common development of secondary porosity due to the pervasive diagenetic process, such as solution and dolomitization. Therefore, pore systems can either be of primary or of secondary origin. The most important and frequently observed pore types of primary origin porosities are interparticle, intraparticle, intercrystalline and fenestral porosities, while for secondary origin moldic pores, vugs, channel and fracture porosities are the most important ones.

1.3 Carbonate porosity classifications

Two major carbonate porosity classifications have been developed to characterize complex carbonate pore systems (Moore 2001): Choquette and Pray (1970) and Lucia (1995) classifications. Choquette and Pray (1970) emphasis is on the relationship of primary rock fabric to porosity and timing of porosity development. This classification is good for geologist and is particularly well suited to geological models that integrate the depositional system with early to late diagenetic process in order to determine porosity evolution through time. On the other hand, Lucia (1995) porosity classification incorporates both rock fabric, which can be related to depositional environments, and the petrophysical characteristics necessary for a viable engineering model. Therefore, it is more suitable for petroleum engineers and petrophysicist (Moore 2001).

In terms of seismic velocities, Wang (1997) classified porosity based on pore types into six categories: intercrystalline and interparticle, moldic and intraparticle, vug porosity, channel porosity, fenestral porosity and fracture and breccia porosity. Interparticle and intercrystalline porosities with primary origin (Choquette and Pray 1970) are usually irregular and angular in shape and easy to deform. They give low velocities and are sensitive to pressure changes (Wang 1997). Intraparticle porosity which forms mainly within individual particles and grains (primary origin) or even by solution and biological boring (secondary origin), gives high velocity and low pressure dependency like moldic porosity (Wang 1997) with secondary origin (Choquette and Pray 1970). Most vugs are equant in size from 1/16mm to 256mm by solution of moulds (Choquette and Pray 1970) and give high velocity and low pressure dependency. If the pores are elongated or openings in the rocks are irregular and elongated, they are defined as channel porosities (Choquette and Pray 1970). Channel porosity is easy to deform and gives low velocity and high pressure sensitivity. Fenestral porosity is developed in algal mats by evolution of gas where there is a gap in the rock framework larger than the normal grain-supported pore spaces (Choquette and Pray 1970). They can be round, lenticular or more irregular in shape and can give high to low velocity in accordance with their shape. Finally, fracture porosity might have the largest effect on velocity and forms through tectonic pressures and collapse of brecciation in carbonate rocks. They are very sensitive to pressure changes and give low velocities.

In general, it is known that velocity and pressure dependency at a given porosity depend mainly on the pore space compressibility. Sometimes high velocity with high porosity is possible if pore compressibility is low. Such a stiff frame is normally found in rocks with vugs or molds porosity but it can also occur in rocks with interparticle and intercrystalline porosity, if for instance, contact cementation exist. The processes that form frame stiffening include cement at grain contacts, like meniscus cements or micritic bridging cements in the marine realm, or even interlocking of dolomite crystals (Eberli 2009). However, the complex geological processes in carbonate rocks may produce pore space compressibility which differ from the ones assumed in the Wang (1997) classification. Paper 1 modifies Wang (1997) porosity classification for chalks as deep basin carbonates in terms of their depositional textural and burial effects. The concept of the new classification is based on foraminifera content and pore aspect ratio transformation according to diagenetic alteration. This paper indicates that discrimination between sediment stiffness and pore structure stiffness enables us to justify low velocity for indurated sediments and high velocity for soft sediments. Furthermore, our results indicate the relevance of the pore structure to velocity interpretation in chalks because some variations in velocity data may result from pore structure differences rather than changes in fluid or porosity.

2. Velocity of carbonate rocks

Carbonate velocity show a positive correlation with density and a negative correlation with porosity, but deviations can be significant at a given porosity (e.g. Anselmetti and Eberli 1997; Rick and Schuelke 2003). Eberli *et al.* (2003) showed that these deviations in P-wave velocity for a given porosity can be as large as 2500 m/s, particularly at high porosities (Fig. 1). Figure 1 shows that different pore types are responsible for such a large scatter in P-wave velocity. The results of Assefa *et al.* (2003) study on limestones confirm velocity differences at equal porosities not only for P-wave but also for S-wave velocities. However, many authors express that these deviations can be explained by the occurrence of different pore types (e.g. Anselmetti and Eberli 1993; Assefa *et al.* 2003; Eberli *et al.* 2003) which can be assigned to specific diagenetic processes and/or their depositional environments (Anselmetti and Eberli 1997). In general, we can say that pore types in carbonates have almost equally importance in the elastic behavior and resultant sonic velocities as porosity (Eberli *et al.* 2003).

2.1 Carbonates elastic behaviors

A number of carbonate core-plug studies have already confirmed the evidence for different pore types by showing that velocity will increase when effective pressure increases (e.g. Nur and Simmons 1960; Wang 1997; Adam *et al.* 2006). The compliant pores and cracks will close by increasing effective pressure, causing the velocities to increase. This pressure dependency behavior of carbonates indicates the existence of different pore space compressibilities as a result of different pore types (Agersborg 2007). Therefore, highly variable pore geometries are normally considered the reason for the complexity in the elastic behaviors of carbonates such as shear weakening or strengthening and modulus dispersion (frequency dependent elastic moduli).

Shear weakening or strengthening is an important phenomenon that is observed in carbonates when exposed to a fluid. Shear weakening or strengthening can be defined as the saturated shear modulus being lower or higher than the dry shear modulus, respectively. Cardona *et al.* (2001) show that sets of aligned open fractures in a rock (anisotropic rock) make variations in the velocity of vertically propagating shear waves due to fluid changes. Adam *et al.* (2006) relate shear weakening to the reduction in surface energy and crack growth while local or global flow produce modulus dispersion and as a result shear strengthening at high frequencies. Baechle *et al.* (2005) consider pore types responsible for such effects. However, the high chemical reactivity of carbonates should have an important role as the chemical interaction between the matrix and pore fluid can either soften or stiffen the rock by altering the porosity and pore types through dissolution and/or cementation.

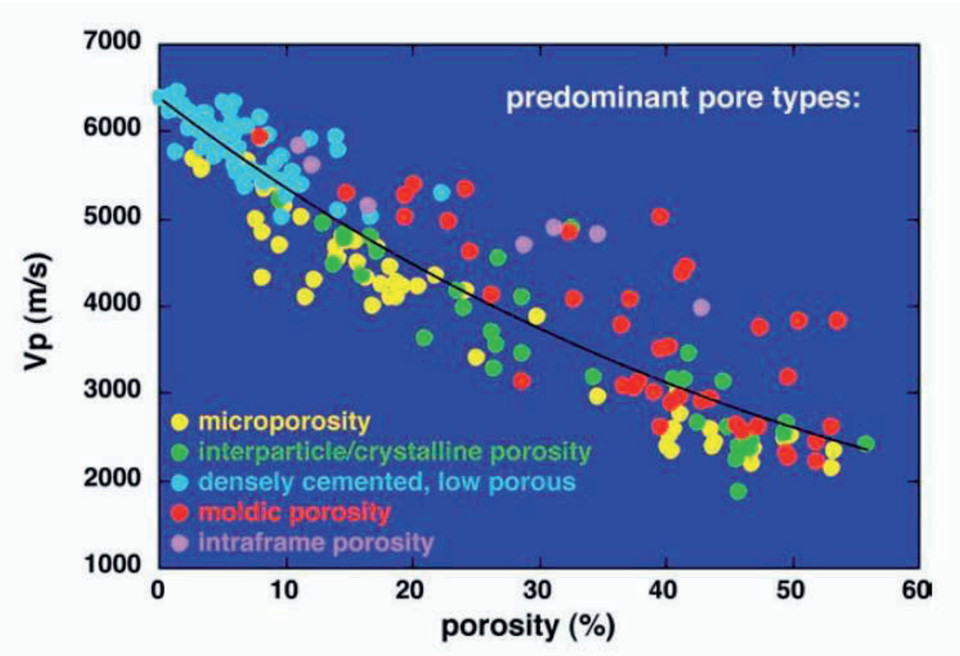

Figure 1 P-wave velocity (V_p) versus porosity for different pore types of carbonate rocks at 8 MPa effective pressures (after Eberli *et al.* 2003).

When comparing ultrasonic with seismic measurements, we have to consider modulus dispersion. Velocity dispersion and attenuation in rocks appears when acoustic waves propagate at different frequencies. The velocity (and modulus), generally increases with frequency and many physical mechanisms have been proposed to explain this phenomenon in rocks (Mavko *et al.* 1998). Among them is wave-induced fluid flow mechanism (local or squirt flow) which can be more prominent in the presence of cracks and compliant pores. Therefore, dispersion effects should be more dominant in carbonates as they are prone to have different pore types (often consisting of cracks and compliant pores). Furthermore, rocks with fractures and very large compliant pores can make this phenomenon to occur even at seismic frequencies (Agersborg 2007).

2.2 Pore structure model

One of the major challenges in carbonate seismic characterization is establishing a quantitative link between pore geometry and elastic properties. Anselmetti *et al.* (1998) introduced a quantitative method for pore space evaluation based on thin-section analysis to quantify and characterize carbonate micro-porosity. But pore type interpretation from thin sections only gives a non-unique subjective (interpreter dependent) description of the pore space and, therefore, can not be related consistently with variations in elastic properties (Colpaert 2007). This is also supported by the Agersborg *et al.* (2009) results which indicate different velocity behavior for pores with micro- or meso-scale connectivity. On the other hand, inversion of seismic velocities or well-log data for pore structure model (e.g. Cheng and Toksöz 1979; Sun and Goldberg 1997; Yan *et al.* 2002), are purely mathematical and difficult to link with the complex geological and reservoir properties observed in carbonate reservoirs. Therefore, fixed values of aspect ratios are often used for carbonate velocity modelling. But the study by Yan *et al.* (2002) shows that elastic moduli have non-linear behavior with respect to the changes in pore aspect ratios (Fig. 2). This indicates the limitation of using fixed pore aspect ratios for small depth intervals over which lithology may be regarded as uniform.

One commonly used assumption for modelling pore structure effects on acoustic properties in carbonates is using the ‘velocity deviation’ term defined by Anselmetti and Eberli (1999) (e.g. Saleh and Castagna 2004; Kumar and Han 2005). This term is defined as the differences between the measured velocities and the time-average equation of Wyllie *et al.* (1956). This quantitative method highlights intervals with frame forming pore types (stiff pores) with strong positive deviations while interparticle and micro-porosities (weak pores) make almost zero or negative deviations. However, the weak correlation for velocity estimates using porosity and digital image parameters for aspect ratios, as been mentioned by Eberli (2009), indicating that aspect ratios may not be the only parameter responsible for variations in the acoustic velocities. Weger (2006), Colpaert (2007) and Eberli (2009) suggested pore size (DOMsize) and complexity of the pores (P/A) as two other parameters that can give a better explanation for the observed scattering on the velocity-porosity crossplots.

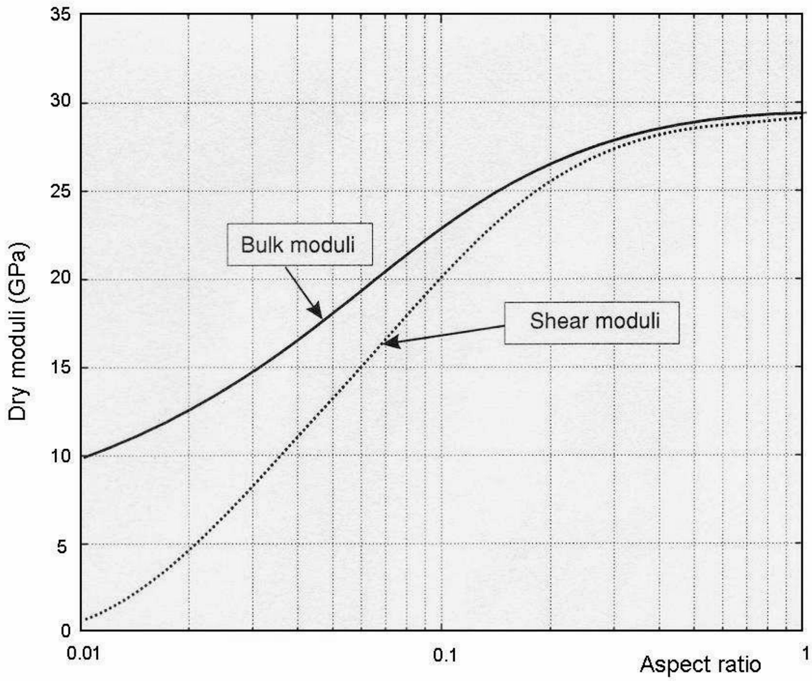

Figure 2 The relationship between aspect ratio and elastic moduli based on Kuster and Toksöz's (1974) model (after Yan *et al.* 2002).

DOMsize is the maximum size of pores needed to occupy half of the pore space on a given thin section, while P/A is the sum of the pore space perimeter over the sum of the pore space area (e.g. Colpaert 2007). Therefore, these two parameters are capable to capture the pore system for numerical elastic modelling (Weger 2006; Colpaert 2007). Colpaert (2007) along with Weger (2006) evaluated the role of these parameters on carbonate velocity behavior. They concluded that carbonate rocks with large and simple pores behave stiffer and thus faster than rocks with small and complex pore systems (Fig. 3).

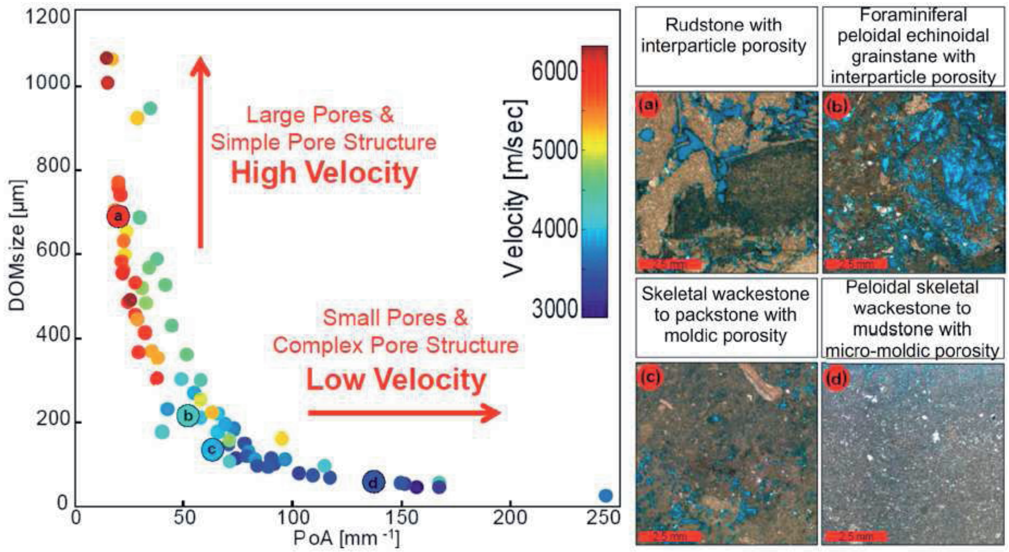

Figure 3 Crossplot of two digital image analysis parameters (perimeter over area (P/A) and pore dominant size (DOMsize)). It shows that carbonate rocks with large and simple pores have higher velocity than those with small and complex pore systems (after Weger 2006 and Colpaert 2007).

Paper 1 introduces the concept of a porosity classification in chalks to define proper pore-models at different depth intervals. This concept, furthermore, is applied in paper 2 to define a pore-model which reflects lithology, porosity and velocity. The approach is to distribute post-depositional state of the sediments at some reference wells to the whole area. Using a simple interpolation method, a spatially varying 3D cube of the pore-model can be constructed. Moreover, this 3D cube pore-model is used to predict velocities at some blind locations. Velocity predictions show a good correlation with measured velocities. On the other hand, paper 4 uses the 'velocity deviation' term (Anselmetti and Eberli 1999) to define a kind of geology dependant pore-model using well log data. The prominent geology effects are incorporated into the pore-models considering velocity-porosity trends for the relevant depositional environments.

3. Rock physics modelling

Rock physics is a bridge between seismic data and the lithology and reservoir properties. It allows a reliable prediction and perturbation of seismic response with changes in reservoir conditions. Therefore, an appropriate rock physics model should be consistent with the available well and core data. Such a consistency can be achieved by adjusting parameters such as pore aspect ratio or even critical porosity that can be determined empirically from the local data. In general, the rock physics models can be divided into three main groups: empirical, heuristic and theoretical models (Avseth *et al.* 2005).

Empirical relationships like Greenberg-Castagna (1992) relations for V_p vs V_s generally assume some functional form and then determine coefficients by calibrating a regression to data (Avseth *et al.* 2005). On the other hand, a heuristic model like time average of Wyllie *et al.* (1956) defines P velocities only from the volume fractions of the various constituents and their velocities. Such a model emphasizes the relationship between various parameters in a certain way through intuitive and nonrigorous means (Avseth *et al.* 2005). Knowing the elastic moduli and volume fractions only enable us to predict the upper and lower elastic bounds like Reuss (1929) and Voigt (1928). If we want to predict the effective elastic properties more specifically, where effects of various geometric details of the constituents are considered (grains and pores), we need to apply theoretical models.

Theoretical models are primarily continuum mechanics approximations of the elastic, viscoelastic or poroelastic properties of rocks. The elastic models include inclusion based theories, contact models, computational models, bound models and transformations (Avseth *et al.* 2005). Among them, inclusion based theories which allow incorporating different pore types using different pore aspect ratios seem to be more adequate in modelling of carbonates (Agersborg *et al.* 2009). But they show strong dependency on the choice of pore aspect ratios. The non-uniqueness also occurs, because a single velocity can be related to different pore aspect ratios. In this thesis, I mainly used inclusion based theories for velocity modelling, and show how to constrain the choice of pore aspect ratios using geology and velocity data at well locations.

3.1 Inclusion based theories

Inclusion based theories model wave velocity and attenuation based on scattering theory and approximate the rock as an elastic block of mineral perturbed by holes (porosity). They generally require the volume fraction of the constituents and physical and geometrical properties of the constituents alone and relative to each other for their solution. Various attempts have been made to account for the scattering effect of each inclusion. These solutions do not commonly depend on pressure and normal/tangential contact stiffness. They may consider just first order scattering term or second and higher order terms.

The first order scattering solution such as Kuster and Toksöz (1974) do not account for pore to pore interactions. While this interactions between pores are considered in the solutions with second orders or higher scattering terms like Differential Equation Medium (DEM) (Nishizawa 1982), self-consistent approximation (SCA) (Berryman 1980a, b) and T-matrix (Jakobsen *et al.* 2003a, b). Therefore, first order scattering models are restricted to handling a dilute volume fraction of pores (lower porosity rocks), and second orders and higher allow for higher porosity rocks.

The DEM approach utilize the principle of porosity growth to extend the results of the first order scattering solution (Kuster and Toksöz 1974) to be valid at high porosities. While SCA consider a uniform host material embedded with spherical and ellipsoidal inclusions (Berryman 1980a, b). However, both approaches simulate high-frequency saturated rock behaviour and, therefore, are appropriate to apply to ultrasonic laboratory conditions. Furthermore, the visco-elastic effective medium theory of Jakobsen *et al.* (2003a, b) (T-matrix) also take into account global and local fluid flow, attenuation due to wave induced fluid flow, anisotropy and various degree of connectivity between pores (Agersborg 2007). Therefore, it can handle modelling with complex situations (e.g. global and local fluid flow effects, different degree of pore space connectivity etc.) more accurately.

4. Carbonate seismic reservoir characterization

Seismic reservoir characterization can be defined as the processes of describing various reservoir characteristics, such as lithology and porosity using seismic data. Seismic signatures change as wave propagates through rocks with varying properties like fluid, porosity and pore types and mineralogy. Therefore, the rock properties affect the observed acoustic and elastic behaviour of seismic data which are recorded by differences in the kinematic (e.g. travel time) and dynamic (e.g. amplitude-versus-offset, AVO) responses.

The complexities in the carbonate rock properties make the application of the seismic reservoir characterization techniques such as seismic inversion (e.g. porosity maps) and amplitude-versus-offset (AVO) analysis uncertain. Hence, procedures and calibrations in seismic data processing and interpretation of carbonates need to be developed for such complexities (Li *et al.* 2003). Revisiting Gassmann's (1951) relations and AVO attributes like fluid factor are some aspects of this challenge. Paper 3 and 4 discuss these issues using a real carbonate dataset from the Barents Sea.

4.1 AVO modelling

Amplitude-versus-offset (AVO) techniques in seismic exploration aim to extract information about lithological conditions and pore fluid properties of subsurface materials from reflection amplitude variations with offset. These techniques are governed by the famous nonlinear equations of Zoeppritz (1919) which gives the behaviour of a reflected seismic wave (reflection coefficient) with angle of incidence at the boundary between two plane layers. However, approximations of the Zoeppritz equations (e.g. Aki and Richard 1980; Wiggins *et al.* 1983) usually are considered for AVO analysis.

The complex rock properties in carbonates, mainly related to their pore structure (Wang, 1997) and multi-scale porosity (Agersborg *et al.* 2009) make standard AVO methods unreliable (Li *et al.* 2003 and 2007). However, studies of Rafavich *et al.*

(1984) and Li and Downton (2000) show significant effects of, e.g., gas on the AVO behavior also in carbonate rocks, which again indicates the applicability of AVO to detect fluid anomalies within water-saturated carbonate sequences. In paper 3, we reevaluate the applicability of one of the AVO attributes, namely the fluid factor for fluid detection in a carbonate layer in the Barents Sea. This attribute is normally used to generate seismic fluid images for siliciclastics in order to highlight the zones with different saturations. Paper 3 modifies the fluid factor equation using a more linearized background trend, and investigates its applicability to an assumed partly gas-saturated carbonate layer in the Barents Sea. The modified fluid factor equation appears less noisy, and also displays the water-gas boundary more continuous compared with other fluid factor equations.

4.2 Fluid substitution

The low frequency approach of Gassmann (1951) is widely used in calculating seismic velocity changes due to pore fluid changes, but several experimental studies on limestones and dolomites (e.g. Wang *et al*. 1991; Nolen-Hoeksema *et al.* 1995; Wang 2000; Røgen *et al.* 2005; Baechle *et al.* 2009) do not to the same extent support the validity of this model. These laboratory measurements either underestimated or overestimated the velocities compared with Gassmann's theory. On the other hand, samples with round pores, vugs and micritic textures were well predicted using Gassmann's relation (Adam *et al.* 2006). Gassmann's derivation is based on several assumptions for a porous medium like mono-mineralogy, homogeneous and isotropic rock with equilibrium pressure between pores (Mavko *et al.* 1998; Adam *et al.* 2006) which may not be valid for carbonates. Adam *et al.* (2006), Baechle *et al.* (2009) and Xu and Payne (2009) emphasize particularly the role of the different pore geometries and, thus, the pore space compressibility on the elastic parameters when pore fluid is altered.

Pore space compressibility is defined as the ratio of fractional changes in pore volume to an increment of applied external hydrostatic stress at constant pore pressure (Mavko *et al.* 1998). This important parameter of a rock provides a robust, modelindependent descriptor of porosity and pore fluid effects on effective moduli, and must be considered in seismic reservoir property modelling. In paper 4 impacts of depositional environments and subsequent diagenetic alterations are considered to define a kind of geology dependent pore-model on 23 carbonate core-plugs from two exploration wells (7128/4-1 and 7128/6-1) in the Barents Sea. Furthermore, pore space compressibility is linked to the pore-model characteristics, and a simplified Gassmann equation along with a similar relationship for shear moduli were used to modify the pore-models for a linear behaviour in their elastic moduli versus fluid bulk modulus. Then, the modified pore-models were used in SCA to model fluid substitution in the same core-plugs, and results were compared with similar results obtained using Gassmann's (1951) model and data from measurements. This paper indicate the role of pore structure on the elastic behaviour of carbonates as pore fluid is changed, and gives an approach for adjusting velocities due to compliant pores.

5. References

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